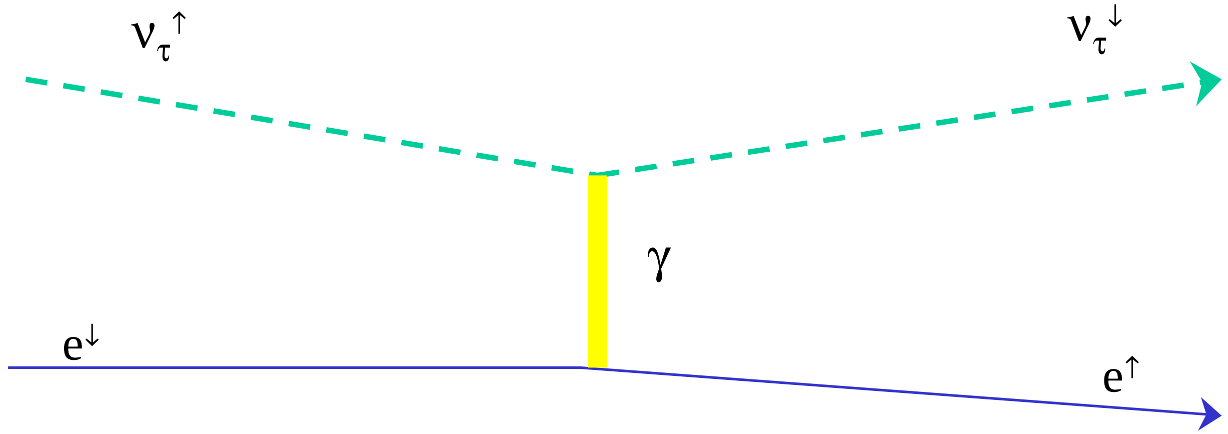
Search for Evidence for a Tau Neutrino Magnetic Moment



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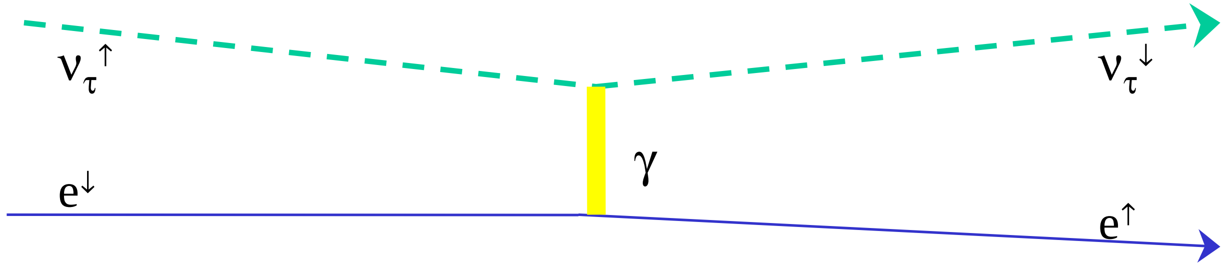
Outline

- Introduction
- Theory
- Analysis steps
- Monte Carlo
- Results (preliminary)
- Remaining issues
- Conclusions
- Outlook

Thesis Goal: $\mu_{\nu\tau}$

- Find interactions that are consistent with a tau neutrino magnetic moment
- if none are found: set a new upper limit for $\mu_{\nu\tau}$
- current experimental limit:
  - ν_e: $\mu_\nu < 1.8\times10^{-10}\mu_B$
  - ν_μ: $\mu_\nu < 7.4\times10^{-10}\mu_B$
  - ν_τ: $\mu_\nu < 5.4\times10^{-7}\mu_B$

Physics process



- ν-e scattering
  - electrons from the atomic shell
- differential cross section

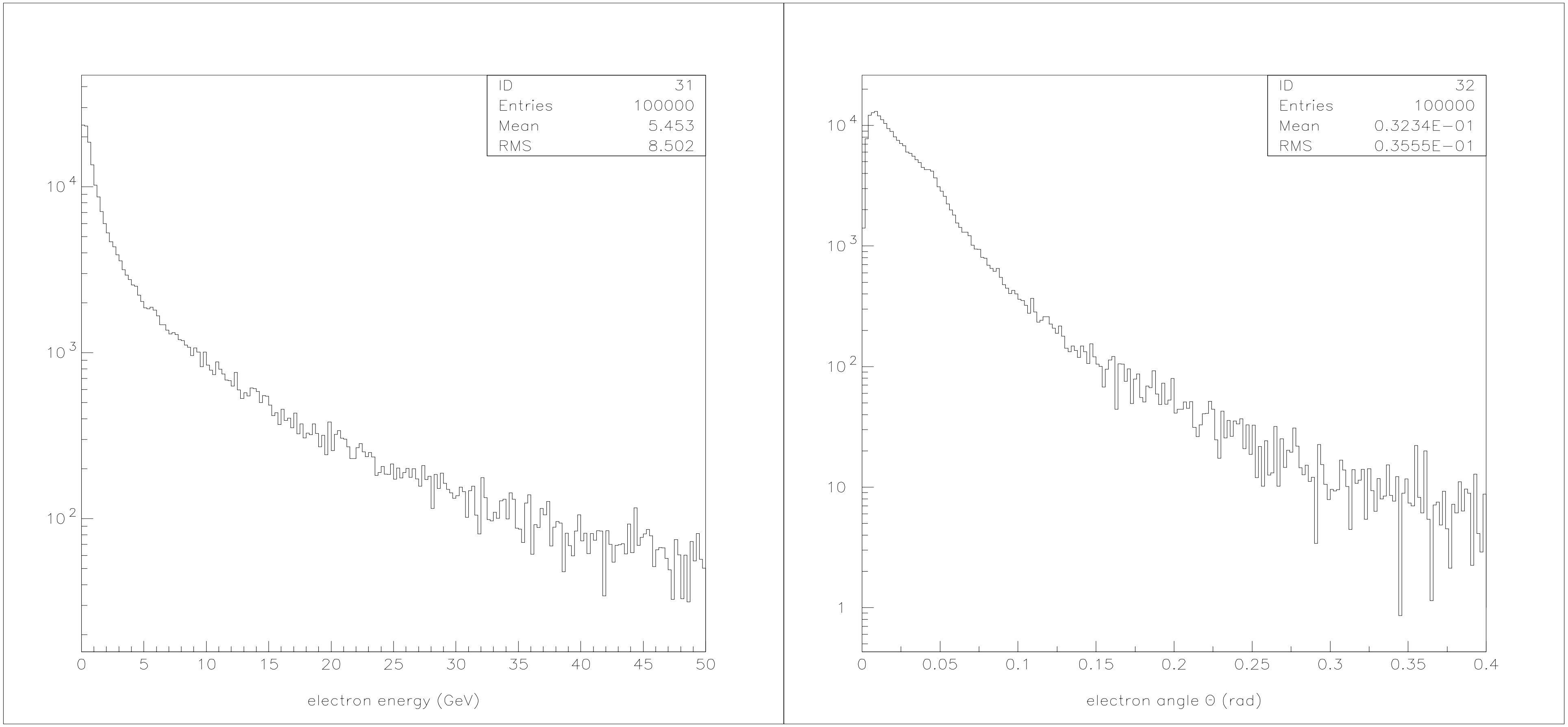
$$\boxed{\sigma^{\mu} = \int_{T_{\min}}^{1} \frac{\mu_\nu^2}{\mu_B^2} \frac{\pi\alpha^2}{m_e^2} \left(\frac{E_\nu}{T} - 1 \right) dT}$$

  - E_ν= incoming neutrino energy; T = outgoing electron energy
- total cross section ~ $\ln(E_\nu/T_{min})$
- event signature:
  production of a single, low energy electron

MC

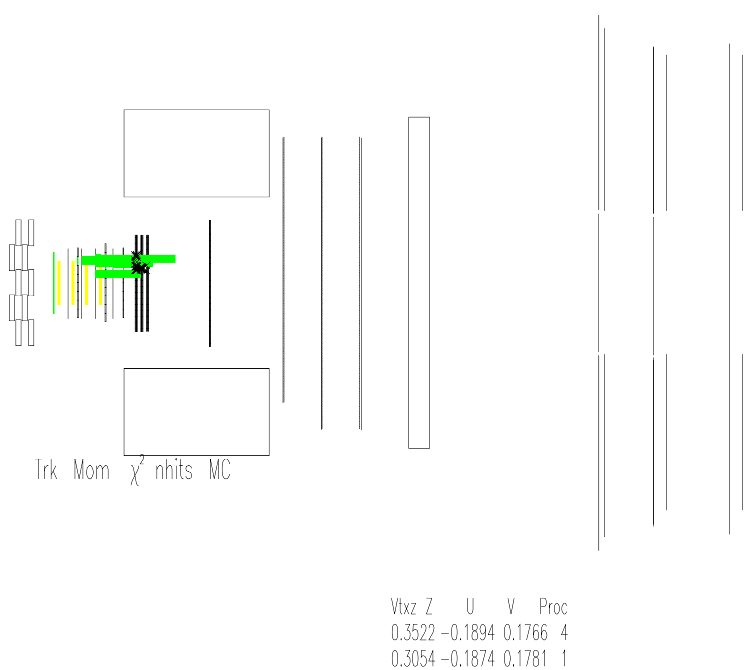
- Standard E872 MC package with
  - magnetic moment scattering routine
    - produce single electrons from ν_τ-electron magnetic moment interactions
  - weigh by $\log(E_\nu)$ instead of E_ν
- trigger acceptance=0.54
  - varies by module

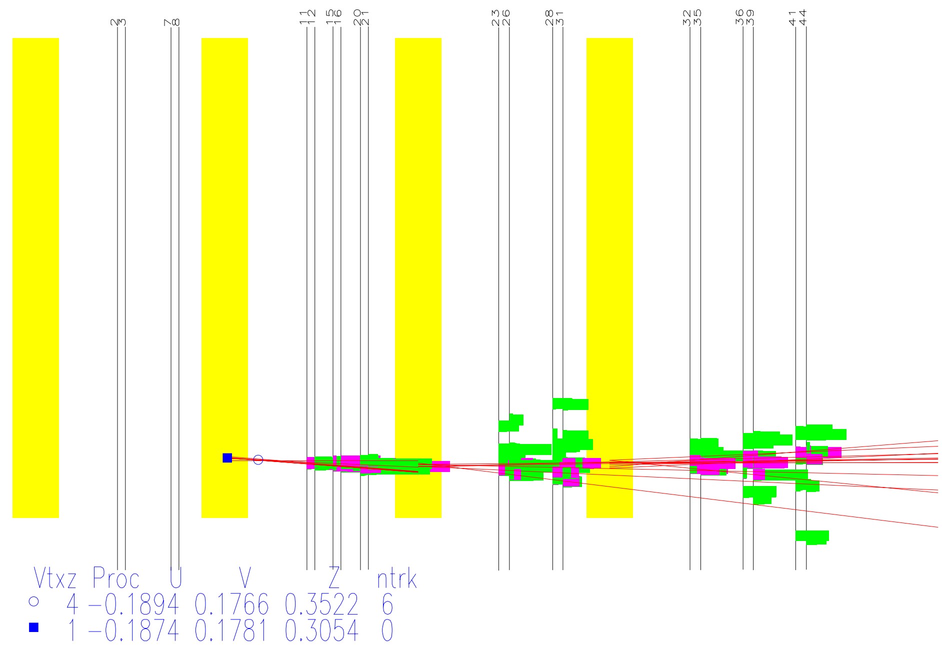
Electron energy and angle



Production angle and energy for the electron in a magnetic moment interaction

Typical magnetic moment interaction





Analysis: Last step, limit for $\mu_{\nu\tau}$

- Limit: $\mu_{\nu\tau} < \mu_{max}$
- μ_{max} is determined by the upper limit for the cross section:

$$\boxed{\sigma^{\mu}_{\max} = \int_{T_{\min}}^{1} \frac{\mu^2_{\max}}{\mu^2_B} \frac{\pi\alpha^2}{m^2_e} \left(\frac{E_\nu}{T} - 1 \right) dT}$$

Step 4: Visible cross section

- The cross section σ^{μ}_{max} is calculated from the visible cross section σ^{μ}_{vis} and the acceptance A

$$\boxed{\sigma^{\mu}_{\max} = \frac{\sigma^{\mu}_{\mathrm{vis}}}{\mathrm{A}}}$$

- An upper limit for the visible cross section is calculated from
  – observed cross section for candidate events (σ_{obs})
  – expected cross section for candidate events for $\mu_{\nu\tau}=0$ (σ_{exp})
  – the total error on the cross section (error_{σ})
- 90% confidence limit for σ^{μ}_{vis}:

$$\boxed{\sigma^{\mu}_{\mathrm{vis}} = 1.64\ \mathrm{error}_{\sigma} + \left(\sigma_{\mathrm{obs}} - \sigma_{\mathrm{exp}}\right)}$$

Step 3: Total error

$$\frac{\text{error}_\sigma}{\sigma} = \sqrt{\frac{\text{error}^2_{\text{obs}}}{\sigma^2_{\text{obs}}} + \frac{\text{error}^2_{\text{exp}}}{\sigma^2_{\text{exp}}}}$$

- The error on σ_{obs} ($\text{error}_{\text{obs}}$) depends on
  - the number of observed candidate events (N_{obs})
  - our knowledge of the total neutrino flux ($\text{error}_{\nu\ \text{flux}}$) and total target mass (error_M)

$$\frac{\text{error}_{\text{obs}}}{\sigma_{\text{obs}}} = \sqrt{\frac{(N_{\text{obs}} - 1)}{N^2_{\text{obs}}} + \frac{\text{error}^2_{\nu\ \text{flux}}}{(\nu\ \text{flux})^2} + \frac{\text{error}^2_M}{M^2}}$$

Step 2: Error on the expected cross section

- Determine with the Monte Carlo
- depends on
  - total neutrino flux and spectrum
  - detector acceptance and efficiency
  - acceptance for the various cuts
  - number of generated MC events

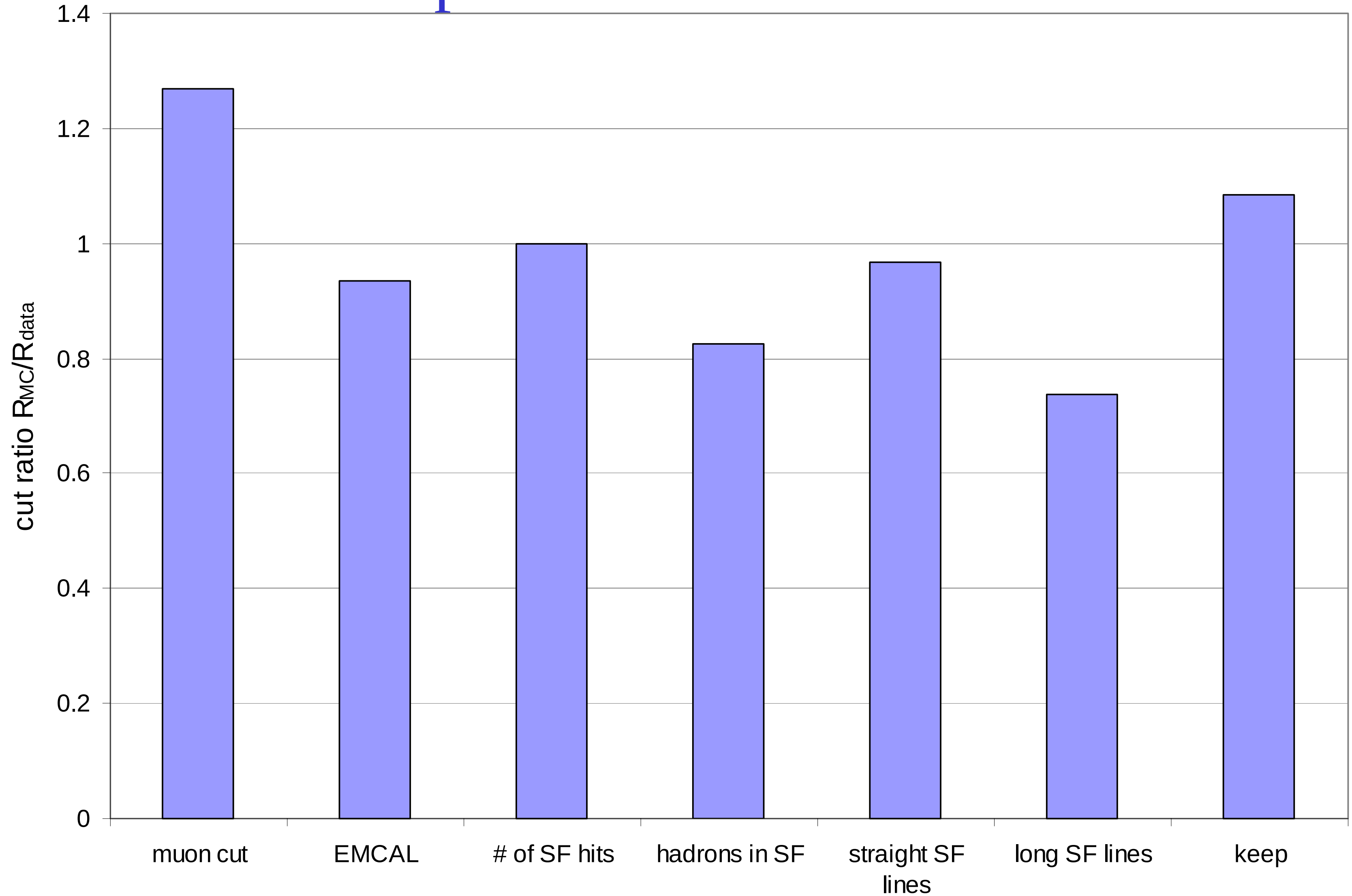
Step 1: Event selection

- Start with .nustrip files
  - Known acceptance (MC)
  - Includes low-energy events
  - many events ↔ few neutrino interactions
- Software cuts
  - Reduce number of events by a factor of 400
  - Acceptance for candidate events is ≈40%
- Visual event classification
  - separate noise from neutrino interactions
  - reduction factor is 7
  - Acceptance ≈90%
- Neutrino event characterization
  - identify CC and NC interactions
  - emulsion analysis

Software cuts

- Remove muons
  - muon ID
  - EMCAL (track P/E)
- Remove hadrons
  - long SF lines (track does not shower in a module)
- Remove ν_eCC events
  - EMCAL energy (>20GeV)
- Remove non-ν events
  - backwards trigger
  - trigger hits behind the vertex
- Require ν-e scattering event pattern
  - straight SF lines (<0.1rad)
  - hits behind the vertex in trigger, VC
  - no energy at the edge of the EMCAL
- Compare MC and data for each cut with ν_μCC events

Check software cuts with ν_μCC events: comparison MC/data



$$R = \frac{\text{cut events}}{\text{all events}}$$

Detailed cuts 1

- Muon ID
  - remove muons and hadrons
  - watch out for noise

  → require <2 MID hits (sum over all tracks)
- EMCAL
  - require E_{EMCAL}<20GeV
  - require for each track with P>4GeV that E_{EMCAL}<P/2 for blocks within 0.2m of the track
  - check the rectangle with $|x-x_{vtx}|<0.7$m and $|y-y_{vtx}|<0.2$m :
    - require at least 50% of the EMCAL energy to be inside the rectangle
    - require the energy outside the rectangle to be less than 1GeV

Detailed cuts 2

- SF system:
  - remove events with:
    - hadrons: highly ionizing tracks (large fiber pulseheight)
    - tracks not coming from the emulsion (muons interacting in the shielding)
    - tracks that go straight through a module (electrons are required to shower)
  - require at least one straight SF line in each view (<0.1rad)
    - put the vertex at the origin of this line
  - require the vertex to be in the emulsion volume

Detailed cuts 3

- Trigger counters:
  - remove backward trigger

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 O O O O O O O O   T1
O O X X O O O O O  T2
 O O X O O O O O   T3
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  - require a trigger panel hit on a straight line behind the vertex
- VDC:
  - require VDC hits on a straight line behind the vertex

Visual event selection

- Output of software cuts is mostly garbage
  - non-neutrino events

→ visual neutrino event selection is necessary

  - analysis of ν_μCC events shows how to get high efficiency
    - be slow and careful
    - don’t throw away the little ones

Event classification

- Remaining events:
  - out of time showers
    - remove if pulseheight in each shower track < minimum ionization
  - neutral current interactions
    - recognize and remove hadrons
      - isolated large pulseheight tracks
      - tracks that enter a module and exit it without producing a shower
  - candidate events
    - keep them

Preliminary result:
of events (in mod 1-3, period 4)

- Observed: 3 event candidates
  - cross section = 3.6×10^{-38}cm^2

  $\rightarrow$ error $\approx$ 60%
- neutrino beam calculation: error $\approx$ 30%

$\rightarrow$ error$_{obs}$=60% (2 events)

- expected: 4 events
  - cross section = 4.8×10^{-38}cm^2
  - most of them NC interactions
- estimated error$_{exp}$ $\approx$ 20% (0.5 events)

$\rightarrow$ error$_\sigma$ $\approx$ 65% (2.1 events) cross section=2.5×10^{-38}cm^2

Preliminary result: cross section (only mod 1-3 in period 4)

$$\sigma^{\mu}_{\text{vis}} = \underbrace{1.64\times 2.5\times 10^{-38}}_{=4.1\times 10^{-38}} + \underbrace{\left(3.6\times 10^{-38} - 4.8\times 10^{-38}\right)}_{<0,\text{ set to }0} cm^2$$

$$= 4.1\times 10^{-38}\, cm^2$$

and

$$\sigma^{\mu}_{\max} = \frac{4.1\times 10^{-38}\, cm^2}{0.62\times 0.4}$$

$$= 1.7\times 10^{-37}\, cm^2$$

- This corresponds to a limit for the magnetic moment of

$$\boxed{\mu_{\nu_\tau} < 3.9\times 10^{-7}\, \mu_B}$$

Issues

- There are many interactions in module 4
  - single hadrons (Alex: N→P)
  - photon conversions
  - low-energy neutrino interactions
    - nonprompt neutrinos
- The detector analysis/simulation need to be improved
  - work in progress
  - EMCAL
  - muon ID
- What is the number of tau neutrinos?

Conclusions

- No evidence for a large μ_{ν_τ} has been found
- We will be able to set a new upper limit for μ_{ν_τ}
  - The limit will be better than the current upper limit ($\mu_{\nu_\tau} < 5.4\times10^{-7}\mu_B$)
- Finding τ neutrino interactions will not improve the limit
  - but it will increase our confidence in the result

Outlook

- I will complete the data analysis for periods 1,2,3
- I will complete the MC analysis
  - calculation of the number of expected events
- I will study the acceptance of my visual selection